A Regional Residential Battery Diffusion Model

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Highlights

1. A novel model of residential battery diffusion with a regional dimension is developed.
2. Long-term simulation of residential battery diffusion in Hungary is performed.
3. Ambitious support is required to achieve substantial system-level impacts.
4. Subsidies accelerate the diffusion but may lead to regional disparities.

Abstract

In this paper, we build a regional simulation model that estimates the diffusion of residential batteries and their impact on the electricity system under different policy scenarios. Most residential battery models do not take into account regional differences, which can lead to inaccurate estimates of residential battery diffusion. Regional differences can occur for a number of reasons (e.g. differences in climatic conditions, income, openness to innovation). This can also be seen in the case of solar panels, where there are significant regional differences in the proportion of households with a solar panel. Imbalances in the diffusion of solar panels and residential batteries can also lead to local imbalances in the grid.

We build a regional diffusion model that projects the number of residential battery adopters, taking into account both financial and non-financial factors. The battery investment decision is made by agents represented by typical load profiles. Each year, the agents decide whether or not to invest in a battery. We study the diffusion of residential batteries in Hungary under different policy scenarios, assuming subsidy frameworks with different levels of ambition. We then assess the system-level impacts of the batteries. Assuming an ambitious subsidy package of EUR 764 million, total residential battery storage capacity can reach 32 GWh and a 3-7% reduction in evening peak load.

Keywords: Battery storage; Technology diffusion; Regional modelling; Electricity system; Load shifting

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1. Introduction

"To unleash further rapid growth of solar and storage and its benefits, we need a comprehensive strategy for electricity storage, and this includes an EU target of at least 200 GW by 2030" [18]. As the share of intermittent renewable energy sources in the electricity system increases, the need for more flexibility is growing. In 2022, there was an 83% increase in residential battery installations across Europe. Most batteries were purchased alongside a PV system, indicating that approximately one out of every four new PV systems now includes a battery [12].

Although there has been increased attention to the system impacts of residential battery storage, there remains a scarcity of literature that comprehensively addresses both the household and the system perspectives, overlooking crucial aspects in the process [2]. A study analyses the influence of Germany's regulatory framework on residential battery storage investments and their impact on the system [8]. Two optimisation models are used: one where households minimise their costs by investing in photovoltaic and battery systems, and another that optimises the electricity system by investing in large-scale generation technologies. However, the study overlooks significant factors. Firstly, it assumes that all households invest once battery storage becomes profitable, ignoring uncertainties and non-financial factors influencing investment decisions, which could be addressed through a diffusion model.

A bottom-up simulation model with real household data from Australia is proposed by [15]. The model determines optimal photovoltaic and battery storage sizes under different tariff schemes. In a subsequent study [16], they expand this approach by integrating household simulation with an optimisation model of Western Australia's electricity system to analyze the effects of increased residential battery storage. However, this model is limited as it only considers a single future year, 2030, making it unable to track the diffusion pathway. [21] examines the impact of residential battery storage in France. It estimates costs and changes in electricity demand if all houses used a photovoltaic and battery system. However, the study overlooks diverse household profiles and solar profiles, assumes direct investments without a diffusion model, and neglects operational strategies' impact.

Several diffusion models were built for residential batteries. European countries are analysed using the ELTRAMOD electricity system optimisation model and a diffusion model to estimate the total installed battery capacities for all countries [10]. [17] use an agent-based model to analyse the diffusion of residential battery storage in California under different policies. However, most studies overlook non-financial drivers in households' decisions and simplify the representation of the Californian wholesale market, limiting its ability to capture long-term dynamics. Finally, [2] propose a novel modelling framework comprising a prosumer simulation and an agent-based electricity market simulation, implemented for Germany and neighboring nations. The prosumer simulation incorporates a calibrated diffusion model, considering non-financial factors influencing households' investment choices. This approach enables a detailed analysis of transformation pathways, considering both households and utilities, and their interdependent perspectives.

However, existing articles typically do not consider regional aspects of residential battery diffusion. The patterns of solar PV distribution prove that PV diffusion is spatially uneven [20]. The intermittency of renewable energy sources causes local problems in the grid; therefore, the regional distribution of residential batteries is crucial. The projection of battery diffusion at regional level can facilitate the planning of infrastructure developments.

This paper proposes a regional simulation model to forecast the diffusion of residential batteries and their impact on the electricity system. The model incorporates both financial and non-financial factors in agents' decision-making, using regional Bass diffusion models. It also considers multiple household and solar profiles. The net present value distribution of battery investment is calculated for each combination of profiles, taking into account electricity usage, climate, labour costs, and battery cost. Then, the results are fed into a Bass diffusion mode to determine the number of battery adopters for each year of the simulation at regional level (NUTS3). Finally, the charging and discharging patterns of the batteries are calculated and their overall impacts on the electricity system.

The model is used to project the number of residential battery adopters in the Hungarian electricity market under different policy scenarios. We consider a baseline scenario with no support for battery installation, a moderate support scenario, and an ambitious support scenario. Additionally, we evaluate the efficiency of two different support frameworks in terms of the overall number of adopters and regional discrepancies.

The remainder of this paper is organized as follows. Section 2 outlines the regional diffusion model and provides a short description of the inputs. This leads into Section 3, where we discuss the different scenarios of residential battery diffusion and their impacts on the electricity system. Finally, Sections 4 summarises our conclusions.

2. Materials and Methods

The proposed regional diffusion model takes into account both the residential and the electricity system impacts of the batteries. The households are represented by a prosumer simulation similar to [2]. Prosumers' investment decision depends on their load and solar profile. The solar profiles and the shares of the different load profiles vary across regions; thus, incorporating regional specifics into the model. At the electricity system level, the changes in the total load curve and the peak shaving potential of residential batteries are assessed.

2.1. Prosumer simulation

The model considers multiple regions, household load profiles and consumption sizes (indexed with r, p, and s respectively). The region determines the solar profile of the households and the labour cost of the battery installation, the load profile determines when the battery is charged and discharged, while the consumption size determines the size of the battery to be installed. The model assumes that batteries are installed alongside solar PVs and charged from excess solar energy. A battery is charged when the solar PV generates more electricity than the household consumes. The size of the solar PV is determined to match the household's annual consumption.

Although prosumers take various important factors into account when making investment decisions, they do not have perfect information on the future benefits of residential batteries. The model simplifies the investment decision to provide a more accurate representation of prosumers in reality. The calculation of the net present value (NPV) involves the following steps.

First, the annual benefit of the battery is calculated by determining the total amount of energy stored in the battery over the course of a year (*EnergyStored*) and multiply it by the efficiency of the battery (*Eff*), the depth of discharge of the battery (*DoD*), and the difference between the electricity price (*ElecPrice*) and the feed-in-tariff (*FeedInTariff*). It is important to note that the daily energy storage is limited by the size of the battery and the depth of discharge, allowing a maximum of one charge cycle per day. The depth of discharge limitation is added to avoid shortening the battery's lifetime.

$$AnnualBenefit_{r,p,s} = EnergyStored_{r,p,s} \times Eff \times DoD \times (ElecPrice_s - FeedInTariff) \tag{1}$$

Then, the discounted benefit of the battery over its lifetime is calculated in Eq. (2).

$$DiscBenefit_{r,p,s} = \frac{AnnualBenefit_{r,p,s}}{r-g} \times \Big(1 - \frac{1+g}{(1+r)^{Lifetime}}\Big) \tag{2}$$

where r is the real discount rate assumed by the prosumers, g is the annual electricity price growth, and *Lifetime* is the lifetime of the battery in years.

After the discounted benefit of battery installation is calculated, investment costs are assessed.

$$InvCost_{r,s} = (BatteryCost + LabourCost \times IncomeAdj_r) \times BatterySize_s \times (1 - Subsidy) \tag{3}$$

where *BatteryCost* price of a battery with 1 kWh storage capacity, $BatterySize_s$ is the assumed battery size in kWh for the corresponding consumption size, *LabourCost* is the installation labour cost, while $IncomeAdj_r$ is an adjustment to the labour cost based on the average income level of the region.

Finally, a normal distribution with mean equal to $DiscBenefit_{r,p,s}$ and with a standard deviation of *CostStd* is generated. The potential population of the Bass model is determined using the probability calculated from the discounted benefit distribution. The share of the total population of a region defined as the potential population in the Bass model in region r in year t is:

$$\begin{aligned} PopShare_{r,p,s} &= 1 - P(DiscBenefit_{r,p,s} \leq InvCost_{r,s}) = \\ &= 1 - \int_{\infty}^{InvCost_{r,s}} \frac{1}{\sqrt{2\pi}CostStd^2} e^{-\frac{(DiscBenefit_{r,p,s} - InvCost_{r,s})^2}{2CostStd^2}}. \end{aligned} \tag{4}$$

However, it is assumed that a small proportion of the population are 'innovators' who invest in new technologies regardless of NPV.

In summary, the NPV calculation determines the percentage of regional households for which the installation of the battery is beneficial. This is then used as the potential population for the Bass diffusion model.

2.2. Bass diffusion model

Although the NPV calculation represents a diverse range of prosumers distinguished by investment cost, consumption size, load profile, and solar profile, financial return is not the only factor influencing the investment decisions. Even if the NPV calculation may indicate that investing in batteries is beneficial, non-financial factors such as insufficient information and uncertainty about the costs of battery storage impede rapid penetration [19]. This aspect is often ignored in the literature, resulting in an overestimation that can be addressed, for example, using the Bass diffusion model [2].

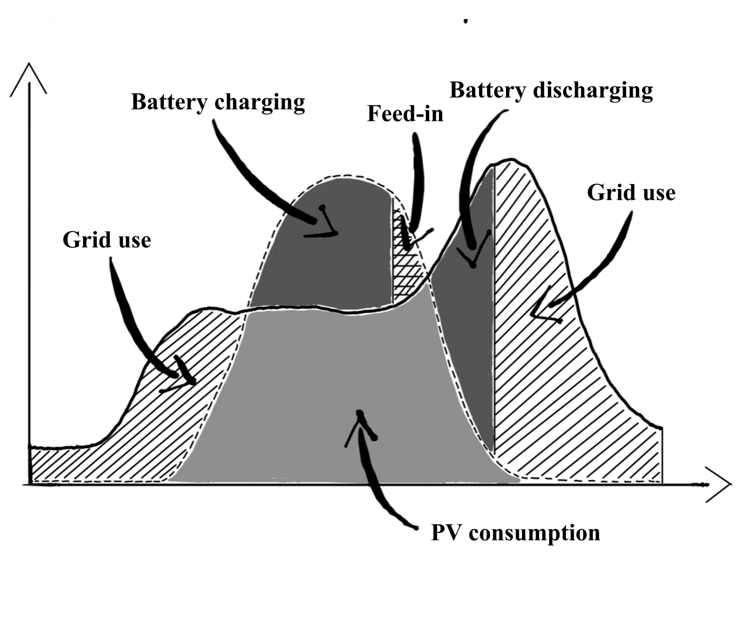
The model employs regional Bass diffusion models, described by Figure 5 to estimate the potential adopters of residential batteries, addressing the deficiency in information on diffusion numbers and representing the regional characteristics of the system. The regional aspect of the analysis is essential from the system perspective as the imbalances caused by the high share of renewables are local problems.

$$N_{r,t} = M_{r,t} \frac{1 - e^{-(p_r+q_r)(t-t_0)}}{1 + \frac{q_r}{p_r} e^{-(p_r+q_r)(t-t_0)}} \tag{5}$$

Each year, the model estimates the number of residential battery adopters in region t ($N_{r,t}$) at regional level taking into consideration the potential population of adopters ($N_{r,t}$), and the innovation (p_r) and imitation parameters (q_r). Since residential batteries are not widespread enough to estimate the innovation and mitigation coefficients, they are derived from the numbers of installations of residential solar PVs. The innovation coefficients are also used to differentiate the number of innovators across the regions. On average, it is assumed that 1% of the population are innovators, and the regional differences follow the relative deviation of the innovation coefficients. The starting year for the diffusion of residential batteries in the residential is set at 2015.

As the potential population of the Bass models changes dynamically from year to year, the hypothetical S-shape curve of diffusion changes. Therefore, each year the model fits the number of residential batteries from the previous year to the S-shape curve corresponding to the actual potential population. It then calculates the additional number of adopters based on this segment of the curve, ensuring the S-shape of the curve.

Figure 1: Schematic overview of the battery operation strategy.



2.3. Battery charging

The charging and discharging patterns of the batteries are estimated at region, load profile, and consumption size level. The output of residential batteries is solved continuously every hour of a year. The model does not assume any incentive for the prosumers to use their batteries to provide flexibility services to the system. Therefore, prosumers are assumed to be profit maximising. The operation strategy of the batteries follows the strategy defined by [2]. The electricity demand of the household is primarily met by the generated solar power. If there is surplus PV generation, it is directed towards charging the battery. If the battery is already at full capacity, the excess power is fed into the grid. In instances where current photovoltaic generation does not meet demand, the battery steps in to supply electricity to the household until it is completely discharged. Any remaining demand, not covered by PV generation or battery discharge, is fulfilled by the electricity grid; there is no exchange between the battery and the grid. The general operation strategy is outlined on Figure 1.

2.4. Data

We demonstrate the model's capabilities using the Hungarian electricity market as a case example. The analysis relies on multiple data sources to accurately represent the situation of Hungarian households.

The main regional characteristics are summarised in Table A.1, while the main parameters of residential batteries are outlined in Table 1. Furthermore, we use three type of household load profiles (general, urban, rural) published by [13]. The proportion of household profiles within a region is determined by the proportion of different types of residential areas[4]. The model assumes three levels of consumption: small, medium and large. The annual consumption of medium consumers corresponds to the average regional consumption, while small consumers consume 75% and large consumers 150% of the average. The 50% of the population are medium consumers and 25-25% are small and large consumers. The battery sizes assumed for the small, medium and large consumers are 3 kWh, 4 kWh, and 6 kWh respectively. Projections of battery price changes are taken from [1]. In Hungary, residential consumers pay a lower electricity tariff for consumption below a certain limit (2523 kWh per year), above which the tariff approximately doubles. Consequently, the electricity price for each profile is calculated on the basis of its annual consumption.

Table 1: Main model parameters of prosumer simulation

Parameter	Value	Sources
Battery cost (EUR/kWh)	550	based on [11][a]
Battery cost relative std. (%)	20	based on [7][b]
Depth of charge (%)	90	[14]
Discount rate (%)	5	[14]
Efficiency (%)	90	[14]
Annual electricity price growth (%)	2	[3]
Electricity price band limit (kWh)	2523	[6]
Electricity price low band (EUR)	0.0953	[6]
Electricity price high band (EUR)	0.1845	[6]
Feed-in-tariff (EUR)	0.0131	[6]
Labour cost of installation (EUR/kWh)	240	based on [11][a]
Lifetime (year)	15	[14]

[a] The cost of the battery and the installation labour cost are derived from the total cost of the battery assumed by [11], assuming a 70-30 split.
[b] The standard deviation of battery installation is derived from the 5$^{\text{th}}$ percentile value and mean of PV project costs in 2022 presented by [7].

The hourly solar PV output by region are taken from the Photovoltaic Geographical Information System [9].[3] The data was collected for the county seats, assuming that the solar profile is the same across the regions.

3. Results and Discussion

In the following, we present the results of the simulation model for Hungary. First, we describe the baseline results including the investment decision of the prosumers, the battery diffusion, and the resulting total output of the installed residential batteries. The baseline scenario assumes no support for the installation of residential batteries. Then, we present several alternative policy scenarios that support the diffusion of residential batteries and show how these developments affect investment decisions and system-level results.

3.1. Baseline scenario

The baseline scenario helps to explain the general dynamics of the model and serves as a basis for comparison with the policy scenarios, as it does not assume any supporting policies.

3.1.1. Prosumer investment simulation

Investment decisions in the model are made by agents at their level. The analysis considers nine agents in total, consisting of three household load profiles and three consumption levels. The load profiles define the pattern of consumption of households throughout the year at the hourly level. Figure 2 shows the average daily load pattern and the 4-week rolling average of daily consumption in Pest.

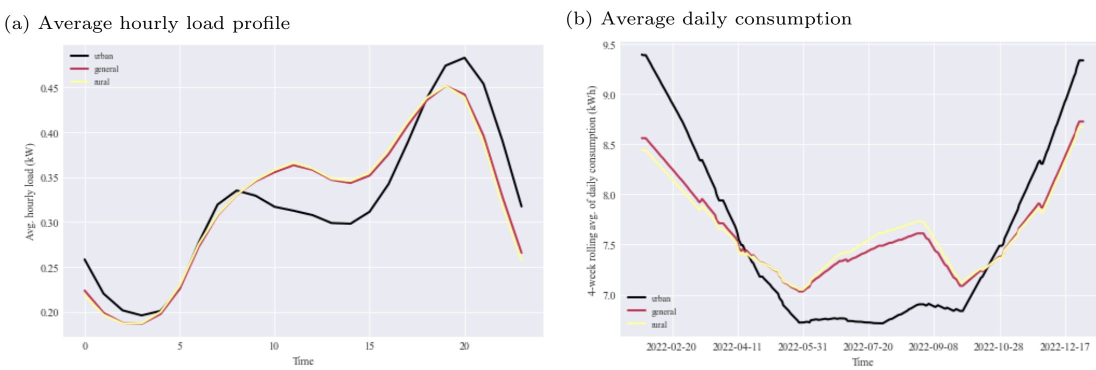


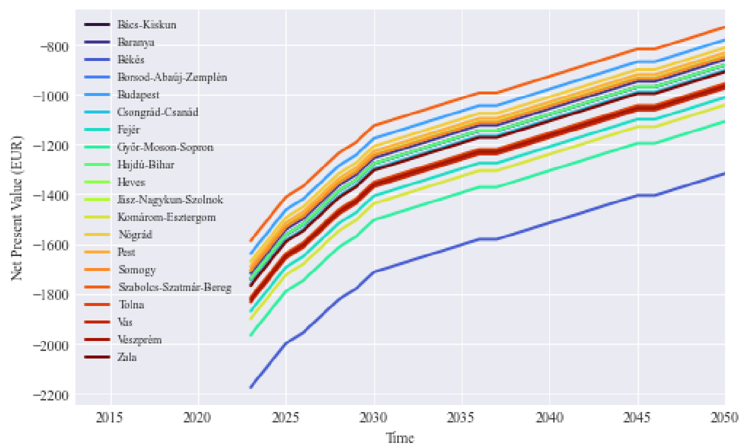
Figure 2: Average hourly load profiles (a) and 4-week average daily consumption (b) by profile in Pest county, source: Hungarian Energy and Public Utility Regulatory Authority and own calculation.

All load profiles show a significant increase in load from 3 pm, reaching the daily maximum around 8 pm. The load then decreases rapidly until around 4 am, when the morning starts. All load profiles also have a peak daily maximum consumption around the end of December/beginning of January. Although the general and the rural load profiles are fairly similar within a day, the seasonal pattern of their consumption differs more. The general profile has a lower peak during the summer, whereas it is higher during the winter. The urban profile; however, has a much higher evening peak compared to the two others, and the seasonal differences are higher as well.

Based on the load and solar profile, the NPV can be calculated to determine the benefits of investing in a battery. Figure 3 shows the evolution of NPVs for general medium-level profiles. While there is an upward trend in NPVs due to falling battery prices and rising electricity prices, all values remain negative in 2050. Therefore, the current electricity prices are insufficient to offset the high initial costs of battery installation, even with a 2% annual growth rate. The NPV values exhibit a consistent trend across all regions, but there are notable variations in their levels. These differences are primarily attributed to consumption and income

[3]The solar PV output was collected with the following parameters: slope = 35°, azimuth = 0°, nominal power of the PV system (c-Si) (kWp) = 1, system losses = 14%

Figure 3: NPV of battery investment with general load profile and medium consumption between 2023 and 2050.



levels, although the solar profile also plays a significant role. Szabolcs-Szatmár-Bereg county has the highest NPV due to above-average electricity consumption and the lowest average income. Conversely, Békés has the lowest NPV due to below-average consumption and the second-lowest solar generation potential.

The NPVs are used in the Bass diffusion models to calculate the potential population. Benefit distributions are created based on the NPV components and the relative standard deviation of battery installation costs (20%). These distributions, along with the share of innovators, determine the proportion of the total population that may invest in batteries. However, the NPV values are well below zero, indicating that only a small fraction of households would invest in a battery without a subsidy, except for the innovators.

3.1.2. Residential battery diffusion

The potential population of the Bass diffusion model, which depends on the NPV of the battery investment, defines the maximum number of adopters. However, the model does not assume perfectly informed and rational prosumers. Therefore, the proportion of the potential population that invests in a battery in a year is determined by the innovation and mitigation coefficients.

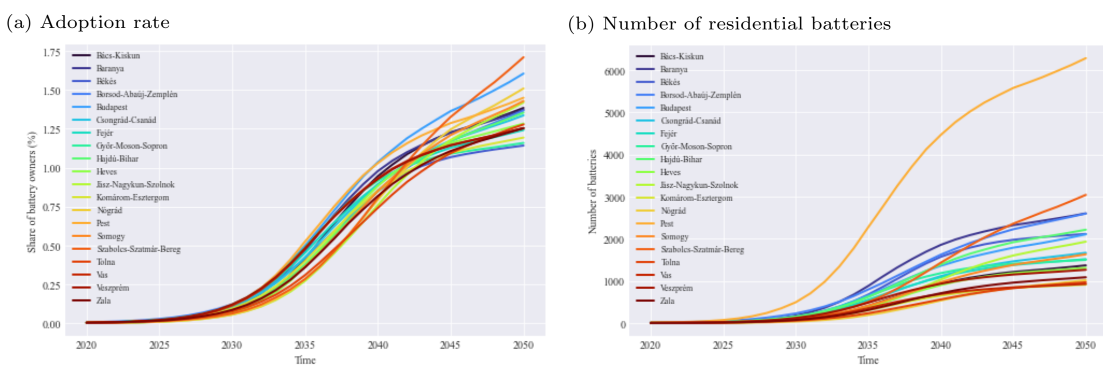


Figure 4: Diffusion of residential batteries by county between 2024 and 2050.

Figure 4 shows the relative and absolute diffusion of batteries at the county level. Adoption rates, expressed as a percentage of the total population having adopted, are very similar across regions. In 2040, the share of battery owners is the highest in Budapest (1.04%) and Pest (1.03%) and the lowest in Tolna (0.74%). The diffusion reaches very similar levels until 2040, as the NPVs are so low in all regions that only innovators and a small fraction of the remaining households purchase batteries. After 2040, however, battery prices continue to fall and a higher proportion of households in the regions with the highest NPVs start to invest in batteries. In 2050, Szabolcs-Szatmár-Bereg (1.71%) has the most battery owners in relative terms, followed by Budapest (%1.61). Figure 4 also shows that diffusion slows down in most regions after 2040, as almost all innovators have already purchased a battery by that time, and the battery investment has not become profitable enough in regions with relatively low consumption.

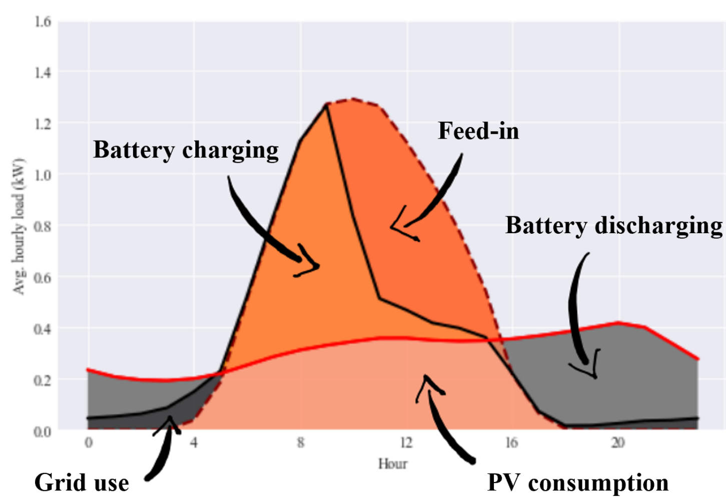
The total number of residential batteries in 2030 is estimated to be around 2 650 in 2030, increasing to 38 000 in 2050. Regional differences are more pronounced in absolute terms. As there are more than twice as many 1-2 apartment houses in Pest county than in any other region (see Table A.1 in the Appendix), the number of battery owners is much higher. This highlights the significance of analysing technology diffusion at a regional level due to the notable differences between regions. The large regions have more potential to introduce batteries and thus increase the flexibility of the electricity system. Furthermore, these analyses help to plan regional grid developments appropriately.

3.1.3. System impacts

Installation of residential batteries can have large-scale impacts on the electricity system. Batteries store energy when solar power is abundant, which can be used later when other energy sources replace solar power, which is currently dominated by fossil fuel power plants. The batteries help to match the households' load on the grid to the availability of solar power. This reduces the imbalance between the overproduction of electricity during the day and the peak load in the evening.

The residential batteries remove supply during the day as they are charged, and remove load during the evening when they are discharged. The average PV generation, load profile and battery operation during the summer is shown in Figure 1. The batteries charge once there is an overproduction of solar energy. By the peak of PV production, the batteries are usually fully charged, and any excess PV generation is fed into the grid, which is in line with the literature [2]. This is usually reached already around 10 am, after which there is a sharp increase in the amount of electricity fed into the grid. The battery charge can usually supply the home until midnight, taking the evening load off the grid.

Figure 5: General load profile with medium consumption in Pest county with battery, summer average.



By aggregating the output of the batteries, we can estimate the overall impact of the batteries on the system. Figure 6 shows the total performance of the batteries averaged over summer and winter. As expected, the battery output is much higher in summer than in winter. During the summer, solar power generation is much higher due to longer hours of sunlight, and batteries can often be fully charged. As can be seen from Figure 1, the batteries take most of the load off the system in the morning hours.

In the early years, the overall impact of batteries is marginal. However, battery installation accelerates between 2034 and 2040, when total residential battery storage capacity increases from 38 MWh to 105 MWh. The total storage potential reaches almost 160 MWh in 2050. In 2050, the peak of negative output, when the batteries are charged, is around 9 am, reaching -24 MW, while the maximum output, when the batteries are discharged, is between 7 pm and 8 pm, reaching 14 MW. In winter, the average power is about half of the summer power, ranging from almost -13 MW to 6 MW.

(a) Summer average (b) Winter average

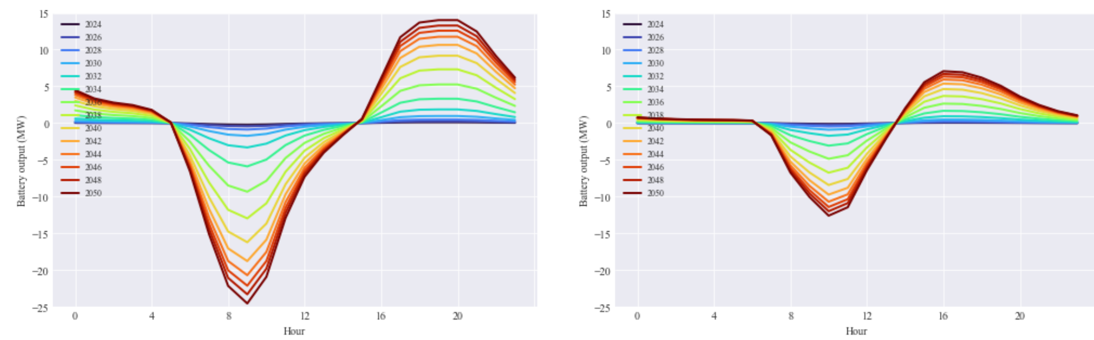


Figure 6: Total output of residential batteries during summer and winter between 2024 and 2050. Negative values indicate the charging, while positives means discharging.

The baseline results showed that without policy support, residential batteries will not be widely deployed and will only marginally contribute to system flexibility. By 2050 only the 1.4% of the target population adopts batteries. The low electricity price and the current high battery prices discourage households from investing in batteries. Therefore, in the following, we present policy scenarios considering different levels and types of subsidies for residential battery installation.

(a) 40% subsidy on costs (b) EUR 680 lump sum subsidy

(c) 50% subsidy on costs (d) EUR 870 lump sum subsidy

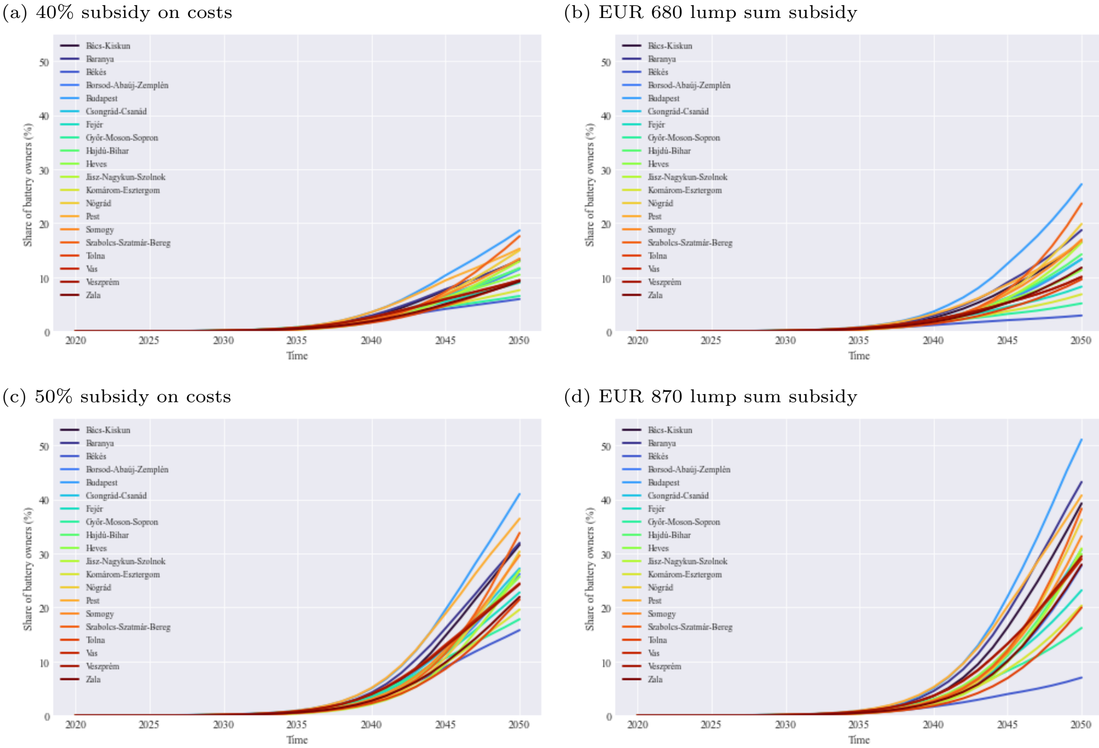


Figure 7: Relative diffusion of residential batteries in different policy scenarios.

3.2. Policy scenarios

To increase the adoption of residential batteries, we examine four policy scenarios that offer substantial support to households. These scenarios include two types of subsidies and two levels of ambition. The first type is an ad valorem subsidy, where the government finances a certain percentage of the average installation costs. The second subsidy involves a lump sum payment to adopters. The first method favours large consumers with high installation costs, whereas the lump sum payment is more advantageous for small consumers, as the payment is the same for all profiles and consumption sizes.

Regarding the level of ambition, we propose two subsidy packages starting in 2024: one with a budget of EUR 268 million and a more ambitious one with a budget of EUR 764 million. The corresponding subsidy levels are 40% and 50% in the case of the ad valorem subsidy and EUR 680 and EUR 870 in the case of the lump sum payment.

The subsidy packages have a substantial impact on the deployment (see Figure 7. Due to the subsidy, more households see the investment in batteries as profitable. Even with the lower budget, the share of battery owners increases almost tenfold. The ad valorem subsidy of 40% leads to a total adoption rate of 12.1% (more than 336 thousand batteries), while the lump sum payment of 680 EUR reaches 14.3% by 2050 both with the same total budget of EUR 268 million. In the same year, the more ambitious subsidy packages with approximately three times bigger budget reaches around 30% adoption rate. The lump sum payment accelerates the battery installation more in the case of the more ambitious package, as well. The lump sum payment of EUR 870 generates almost 100 000 more batteries than with 50% support.

Although the lump sum seems to be more efficient, the regional differences are more pronounced, especially in the ambitious scenario. The range of adoption rates is 44 percentage points, while in the 50% subsidy case it is 25 percentage points. The lump sum payment makes battery investment more profitable in regions with higher NPVs, but in Békés, where the NPV is the lowest, diffusion does not take off, and the adoption rate is only 7%.

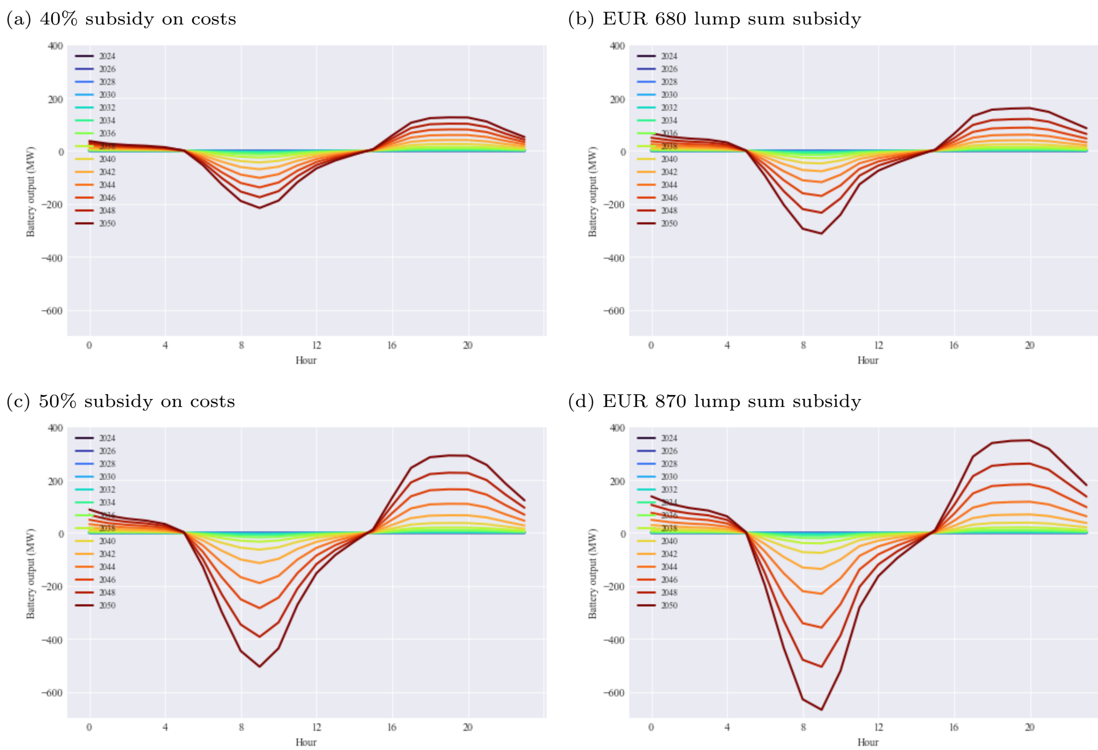


Figure 8: Total output of residential batteries during summer between 2024 and 2050. Negative values indicate the charging, while positives means discharging.

The average total battery output during summer, shown in Figure 8, illustrates the importance of battery support from a system perspective. While in the baseline case the total battery output is marginal, in the ambitious support scenarios the load removed during peak hours is more than 300 MW. In the EUR 680 lump sum scenario, with more than 32 GWh of residential battery storage capacity, the total output ranges from -670 MW to 350 MW. For comparison, the average load in summer 2023 in Hungary is 4470 MW, with an average daily maximum of 5290 MW. There is a slight difference in the pattern between the ambitious scenarios. As the lump sum payment is a better incentive for smaller consumers, in the EUR 870 scenario relatively more 3 kWh batteries are used than in the 50% scenario, therefore the batteries are charged earlier and there is a sharper increase in output after 9 am.

Furthermore, it is also clear from both Figure 7 and Figure 8 that even after 2040 there is still a sharp increase in the uptake of residential batteries. Peak output still increases with almost 90 MW between 2048 and 2050 in the EUR 870 scenario. Therefore, by providing sufficient support to households to install batteries, they can be made available to most potential households and have a significant system-wide impact that can improve the flexibility of the grid.

Finally, we look at the system-level impacts relative to the current total load in Hungary in 2023. This helps to put the overall impact of the batteries into context. The average summer load in 2023 was 4470 MW and the average winter load was 5360 MW. Therefore, the total output of the residential batteries in the policy scenarios in 2050 is comparable to the total load. However, the timing of charging and discharging is important from a system perspective. The total load curve and the policy scenario load curves adjusted with the corresponding battery power in 2050 are shown in Figure 9. Charging and discharging the batteries essentially shifts the evening peak to the morning hours. This adjustment to the load pattern is a good illustration of how batteries can help to shift the load to the availability of intermittent renewables. The evening peak load in summer (around 17:00) is 6% lower in the EUR 870 scenario and 5% lower in the 50% subsidy scenario. However, in winter, when the total load is much higher, the impact of batteries is more modest at 3% and 2.3% respectively. This result highlights the importance of long-term storage capacity, but is beyond the scope of this study.

The operation of the residential batteries has a huge influence on the system level impacts. In the current analysis, the model assumes that the batteries start charging immediately when there is an oversupply of solar power and discharge when there is not enough to meet demand. However, similar to [2]m, different operating strategies could be explored to optimise the use of batteries. The alternative operating strategies could further improve the system benefits of batteries, meaning that the current peak reduction results are likely to underestimate the potential impact of the storage capacities calculated in the policy scenarios.

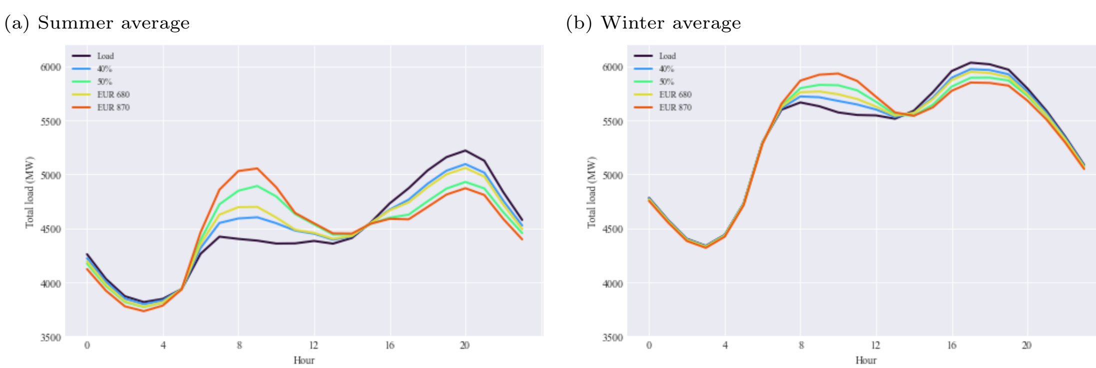


Figure 9: Total load curve in 2023 and adjusted total load curves in summer and winter, assuming the number of residential batteries in the policy scenarios in 2050, source: ENTSO-E and own calculation.

4. Conclusions

The energy transition imposes great challenges on the grid. The increasing share of intermittent renewable energy sources leads to imbalances in the system; therefore, flexibility must be improved. Residential batteries can help both to decrease the oversupply of solar energy during the day and to shave peak load in the evening.

In this paper we presented a novel residential battery diffusion model that estimates the diffusion of batteries considering regional characteristics. The model's abilities are demonstrated using the Hungarian electricity market as an example. The primary outcome of the modeling exercise indicates that, without subsidies, residential batteries will have a limited impact on grid flexibility. The considerable upfront costs are not offset by the comparatively low electricity prices in Hungary. Offering substantial support can expedite battery installations and enable significant storage capacities to be established by 2050. However, the manner in which support is provided is crucial. While lump sum payments result in a higher overall percentage of battery adopters, regional variations are more pronounced compared to proportional support based on installation costs.

Statement of exclusive submission

This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first four months after its submission to the Publisher.

Data availability

Data will be made available on request.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used DeepL in order to improve readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

Declarations of interest: none

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5. Appendix

Appendix A. Data appendix

Table A.1: Summary of regional inputs, source: Hungarian Central Statistical Office, Hungarian Energy and Public Utility Regulatory Authority

County (NUTS3)	Nr. of 1-2 apartment houses [4]	Net income (Ft) [4]	Electricity consumption (kWh) [4]	Nr. of PVs [5]
Bács-Kiskun	189 985	292 438	1 902	10 865
Baranya	98 863	286 499	1 637	8 126
Békés	131 114	255 655	1 759	6 366
Borsod-Abaúj-Zemplén	189 557	271 297	1 683	9 417
Budapest	184 974	422 052	1 790	14 254
Csongrád-Csanád	124 757	294 772	1 754	9 092
Fejér	122 058	333 636	1 881	9 363
Győr-Moson-Sopron	129 292	357 758	1 834	10 000
Hajdú-Bihar	163 536	286 271	1 880	10 104
Heves	102 133	314 155	1 930	4 506
Jász-Nagykun-Szolnok	136 001	277 126	1 883	4 825
Komárom-Esztergom	76 341	337 948	1 969	4 633
Nógrád	67 426	265 437	1 993	2 386
Pest	433 263	309 942	2 340	32 263
Somogy	114 137	275 255	1 570	6 274
Szabolcs-Szatmár-Bereg	177 715	241 855	2 009	7 521
Tolna	75 709	317 790	1 997	3 912
Vas	73 967	313 062	1 750	5 294
Veszprém	100 759	307 603	1 624	7 662
Zala	86 652	277 055	1 386	4 729